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Effects of a Structured Prototyping Strategy on Capstone Design Projects

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Effects of a Structured Prototyping Strategy on Capstone Design Projects

by

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Thesis

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

Master of Science in Engineering

The University of Texas at Austin

May 2015

Dedication

This thesis is dedicated to my parents who are my inspirations and have instilled in me the importance of humility and hard work.

Acknowledgements

I have had the privilege of working with several great professors and students during my time at The University of Texas at Austin. Firstly, I would like to thank Dr. Richard Crawford who served as my graduate adviser. His wealth of experience, his sharp insights and his patience has guided me throughout my research. Also I would like to thank Dr. Jensen at the United States Air Force Academy for playing an important role in my research .His precise edits greatly improved by written work.

I am also grateful to my fellow students Brock Dunlap and Mike Orr who I have had the privilege of working with during my time at The University of Texas at Austin.

Abstract

Effects of a Structured Prototyping Strategy on Capstone Design Projects

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The University of Texas at Austin, 2015

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Prototyping is often a very important phase in a capstone engineering design project. However, in many cases, prototyping decisions are made arbitrarily by students, adversely affecting the quality of the final product delivered. Previous research efforts at The University of Texas at Austin have developed a structured prototyping strategy tool based on a synthesis of prototyping techniques that have been shown to be effective. This strategy tool leads designers through the process of making decisions about aspects of a prototype program, such as how many concepts to prototype, the number of prototype iterations to complete for a given concept, and whether to use scaled prototypes. In this study the effect of explicit discussion of these prototyping decisions on the results of the capstone design projects was evaluated. Research suggests that early and frequent prototyping leads to increases in the quality and the novelty of designs. Therefore, the goal of this project was to determine if exposure to the prototyping strategy tool leads to an increase in the number of prototypes constructed. At the beginning of the semester, students in the capstone course received instruction on the benefits of prototyping and on the use of the prototyping strategy tool. Interviews were conducted at the end of the semester to evaluate the students' prototyping efforts. These results were compared to previous capstone projects where the students did not receive formal guidance on making prototyping decisions. The results of the comparison show statistically significant increases in the proportion of teams opting to create prototypes and the average number of prototypes per team. This thesis describes the study in detail, analyzes the results, and presents conclusions and future directions for the research.

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CHAPTER 1: THESIS OVERVIEW

This thesis contains the research findings from a study to determine the effects of exposure of capstone design students to a well-defined prototyping strategy development tool. Prototyping has long been recognized as one of the most important stages of the product development process (1). Prototyping is the process of generating an initial manifestation of a design concept during the phases of concept generation and design verification.

The product development process often constitutes a huge investment which must be offset by creation of a successful end product. From a financial standpoint it is very important that time and money invested in product development yields a successful product which can be launched into the market. However, an analysis of R&D spending finds that about 40-60% of R&D investment is lost in developing products which are never launched in the market or which do not yield adequate returns (2). The study also suggests that effective prototyping decisions (e.g. how many concepts to prototype simultaneously, how many iterations to pursue for a particular design concept) are critical aspects of a product development process and its success. When a design is prototyped effectively it is simulated without committing the time and cost of full production. Prototypes can also serve as efficient tools to communicate design to non-technical audiences. Research conducted to investigate the relative importance of different product development cycles has shown that prototyping plays a key role in determining the outcome (1). Many companies do not have a structured way to implement the prototyping decisions. Over the course of the last two years a research group at The University of Texas at Austin (UT Austin) has attempted to create a concise prototyping strategy (3) . The research philosophy is that a structured prototyping strategy can provide an efficient way to implement prototyping. The prototyping strategy tool guides the engineering product development teams through six critical prototype strategy choices, namely:

1) How many concepts should be prototyped?
2) How many iterations should be built?
3) Should the prototype be virtual or physical?
4) Should the subsystems be isolated?
5) Should the prototype be scaled?
6) Should the design requirements be temporarily relaxed?

Similarly the prototyping carried out in capstone design classes at UT Austin is implemented in an arbitrary ad-hoc manner. When previous capstone projects were studied it was realized that most of the students finalize their design concept with little to no physical validation. This research was motivated by the premise that capstone design project students will benefit from being exposed to a structured prototyping strategy to both understand the importance of prototyping and provide an efficient way to implement it.

This strategy was presented to students in the capstone design class in a structured manner. The chief goal of this research was to gauge whether exposure to a structured prototyping strategy tool convinces designers of the importance of prototyping and eventually leads to the creation of more prototypes. This study intended to determine if exposure to the prototyping strategy tool is positively correlated to the number of physical prototypes built by the undergraduate students in the capstone design project. The inherent assumption in gauging the success of the design project is that a greater number of physical prototypes result in a better overall design. In other words each physical prototype iteratively improves the design. Hence, the design project is better served by having as many physical prototypes as possible. This obviously must be offset by the constraints of schedule and budget.

The key hypotheses to be tested by this study were:

1) Does exposure to the prototyping strategy tool lead to more prototypes?
2) Does exposure to the prototyping strategy encourage teams who not required to submit prototypes as deliverables to make them nonetheless

To test these hypotheses, the prototyping strategy tool was presented to undergraduate students in the capstone design class of the Department of Mechanical Engineering at The University of Texas at Austin. The study was conducted over two semesters. The presentation was given the beginning of each semester by two graduate students. The details of the study conducted are discussed in chapter 3. At the end of the semester the students' prototyping effort was collected via a survey administered by graduate students. These students served the role of the experimental group. The data collected was compared to data gathered about the prototyping efforts made by a control group of earlier teams who had not been exposed to a formal prototyping strategy development method. To gain information regarding the prototyping effort of the control group, their project reports were studied. The reports contained information regarding the entire product development process followed by these teams, including the number of types of prototypes constructed. On comparison the data shows highly encouraging results as both the average number of prototypes and the proportion of teams opting for physical prototyping increased with statistical significance. The increase in the number of prototypes is important as prototyping early and often has been shown to improve the likelihood of product success (4; 5; 6; 7; 8). This thesis documents the study, the results, the conclusions and the future scope of research.

1.1 THESIS ORGANIZATION

The second chapter covers the background and motivation for undertaking this thesis along with the associated literature survey. The chapter goes in depth into the background of prototypes in general including types of prototypes, functions of prototypes and the advantages of making a prototype. It also talks about the research carried out in the area of prototyping in general and prototyping in the context of capstone design projects in particular.

The third chapter covers the actual research study conducted to answer the research hypotheses. The study conducted in capstone design classes to analyze these hypotheses is covered in detail including the basic approach, the methods used to collect the data, the inherent assumptions and the methods used to analyze the data. This chapter also contains details of the prototyping strategy tool used to analyze the hypotheses and its development. The fourth chapter presents the analysis of the data collected and the final chapter covers the summary conclusions and future work.

The ultimate goal of this research effort is to improve engineering education. The presented prototyping strategy tool allows students hands on exposure to a structured prototyping strategy developed from an engineering standpoint. The research aims to encourage students to pursue prototyping to develop better products. Successfully executed capstone projects will go a long way in preparing future designers of tomorrow and this research is a significant step in that direction.

CHAPTER 2: BACKGROUND, MOTIVATION AND LITERAUTURE SURVEY

Prototyping is the creation of fit, form, or functional design which enables designers to communicate, test, or validate design ideas (9). Prototyping decisions are often implemented based on business considerations rather than sound engineering reasons. Research has shown that the prototyping process requires a large share of the funds invested in a product development process (2). For this reason alone, prototyping should be recognized as an important stage in product development.

Before describing the research study that is the focus of this work, this chapter discusses prototyping in general, the associated terminology and the roles played by prototyping. The chapter also provides a summary of relevant literature related to prototyping research.

2.1. DEFINITION OF A PROTOTYPE

Several definitions of what constitutes a prototype have appeared in the literature. Some authors define prototypes as design models which allow continued development and change to occur in the design process. Other definitions suggest that prototypes are test components which allow designers to implement and test their designs (10) (11). Researchers have also suggested that physical prototypes can be used to resolve issues during product development (9).

A prototype can also be said to be a design representation of some aspect such as form/fit or function of a design. This broad definition allows any representation including sketches, twist tie models or cardboard cutouts to be classified as prototypes. Any model of the final product which communicates the product's look and feel or the visual layout as such can also be called a prototype. Prototypes can be models which allow for the exploration, optimization and validation of the mechanical hardware.

Despite this broad general definition of a prototype, the nature of the current study limits the use of the word "prototype" in the context of this thesis. The primary focus of this research study is to investigate a possible increase in the number of physical prototypes made to validate student designs. Hence from chapter 3 onwards whenever the word prototype is mentioned, it is referring to a physical representation of the model and should not be confused with the broad range of prototyping definitions presented above.

2.2. PROTOTYPE CLASSIFICATION

Prototypes can be classified on the basis of several different aspects. Some attempts have been made to classify prototypes on the basis of cost and stage of design (5). Some have also focused on the level of abstraction and realism. There also have been attempts to classify prototypes according to their intended evaluation purpose. Prototypes have also been regularly classified as virtual or physical. Since this research primarily focuses on the advantages of physical prototypes it is important to understand the different types of physical prototypes and consider the advantages/disadvantages of each type. Otto and Wood (10) have identified six general classes of physical prototypes:

1. Proof of concept models
2. Industrial design prototypes
3. DOE experimental prototypes
4. Alpha prototypes
5. Beta prototypes
6. Preproduction prototypes

Each of these is discussed below. Figure 1 depicts the different types of prototypes that are discussed.

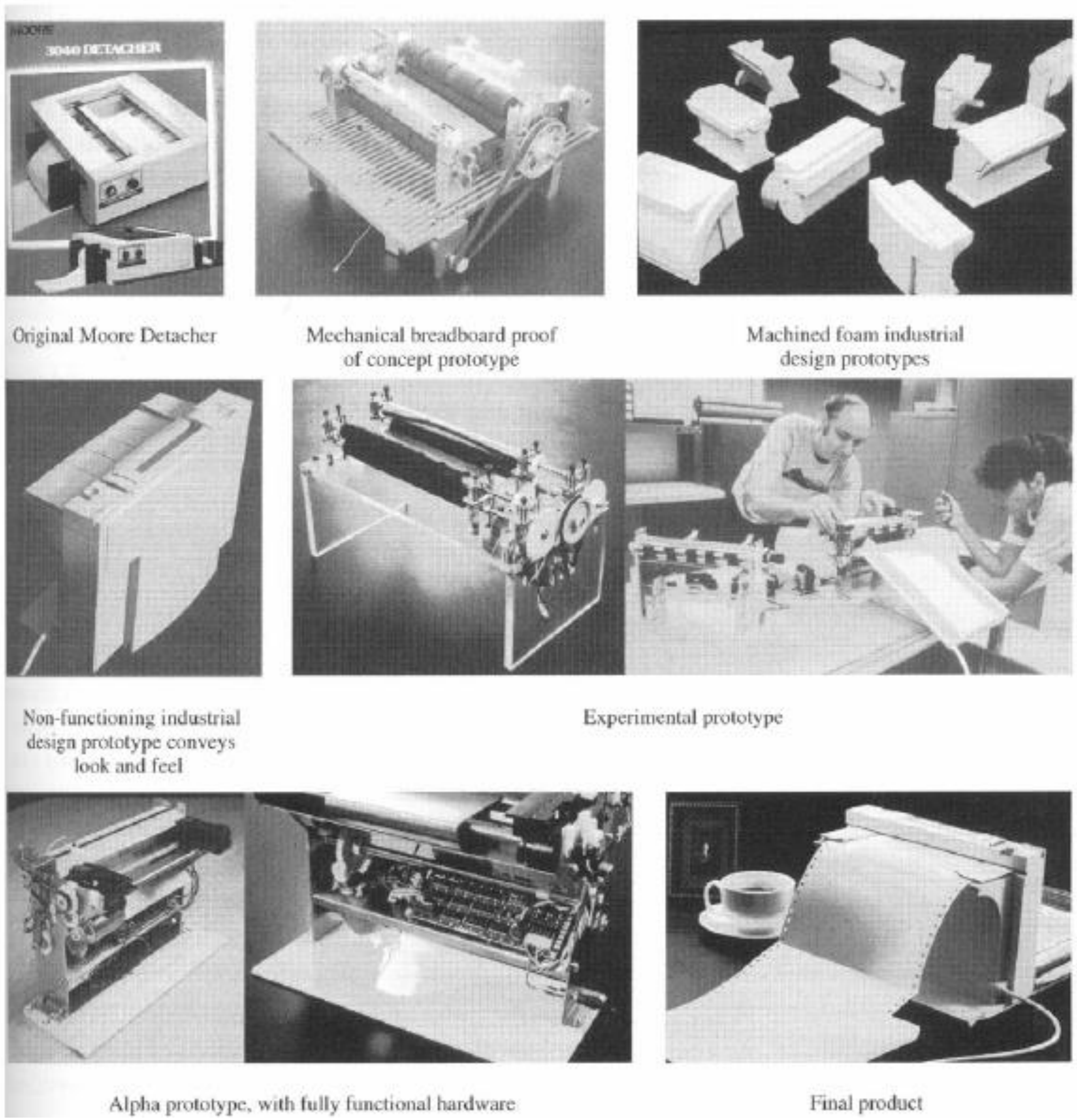

Figure 1: Types of prototypes for a printer page bursting product (10)

2.2.1. Proof of Concept Models

These prototypes are used to answer specific questions regarding the feasibility of a particular concept, usually during the concept generation/selection or early embodiment phase of design. They are preliminary prototypes that are constructed using readily available materials. They generally provide verification of the physics of the concept, to a first approximation.

2.2.2. Industrial Design Prototypes

These prototypes are generally used to demonstrate the look and feel of the product. Like proof of concept models, they are generally fabricated from simple materials and are intended to compare several options as quickly and cheaply as possible. The industrial design prototypes look exactly like final products but are often made from plastic or foam blocks and have no internal working components. These types of models are particularly important for products where the external appearance plays a major role in gauging the quality of the final product, such as automobiles or high-tech consumer products.

2.2.3. DOE (Design of Experiments) Experimental Prototypes

These prototypes are created to obtain empirical data to parameterize function, layout, or shape aspects of the product. These models may be focused on a particular subsystem to understand the relationships between design variables and performance parameters. When the focus is on function, these prototypes often look nothing like the final product.

2.2.4. Alpha Prototypes

These prototypes are closer to the actual final product, usually included all of the intended functionality of the product. An effort is made to use the materials, geometry, and layout of the final product. Alpha prototypes can also serve the purpose of testing and measuring the performance of critical aspects of the system.

2.2.5. Beta Prototypes

These are first full scale functional prototypes of a product which are constructed from the actual materials of the final product. They may not necessarily be manufactured from the same production processes as the final product.

2.2.6. Pre-production prototypes

Small batches of the product are fabricated to evaluate the manufacturing process and to verify product performance for full scale production. Generally a systematic statistical quality analysis is carried out on pre-production models before commencing full scale production.

Since most of the projects in the capstone design class are only semester long projects it is unlikely that any of the teams will elect to make a pre-production prototype. Previous design reports suggest that most of the prototypes made are either proof of concept models or alpha prototypes.

2.3. PROTOTYPING ROLES

Given the high importance to prototyping in the context of this research, the roles played by prototypes in the product development process should be clearly understood. A case study validation conducted in Clemson University (9) has developed a classification scheme for prototypes on the basis of the broad roles fulfilled, particularly by physical prototypes.

Learning

In this context prototypes can be used to assess performance with respect to design requirements. Physical prototypes are most suited to fulfill this role as they most accurately resemble actual performance. They can act as open systems as they are affected by all physical parameters regardless of whether the designer took into account those factors while designing this product. A designer generally creates a non-physical prototype as a closed system. Hence any shortcoming in the designer's understanding of the model may not manifest itself in a non-physical model. That is why physical prototypes are almost unavoidable in the design of mechanical systems. Examples of learning prototypes are test prototypes which make sure all systems work as per design intent.

Communication

Prototypes can be used to convey information beyond the design group. They act as methods of communicating information regarding project understanding, functionality, performance and other variables. Physical prototypes can be very useful for communication purposes as they provide three dimensional representations of the expected designs, which are more expressive than two dimensional representations.

Integration

When individual components have been tested separately it is essential to ensure that the prototype works as intended when it is assembled as a whole. This can be also used to verify the assembly process for the entire model. With increased functionality in virtual modelling, CAD and FEA simulations are increasingly used to test this aspect of the model.

Demonstration

A prototype can be used as a method to demonstrate the capability or indicate steady progress towards the final product. Especially for projects in the mechanical engineering domain physical prototypes are universally regarded as appropriate for purposes of demonstration. Some common examples of physical prototypes used for demonstrations are proof of concept, proof of product, proof of process and proof of production.

A more detailed classification of the prototyping roles can be found in figure 2 below.

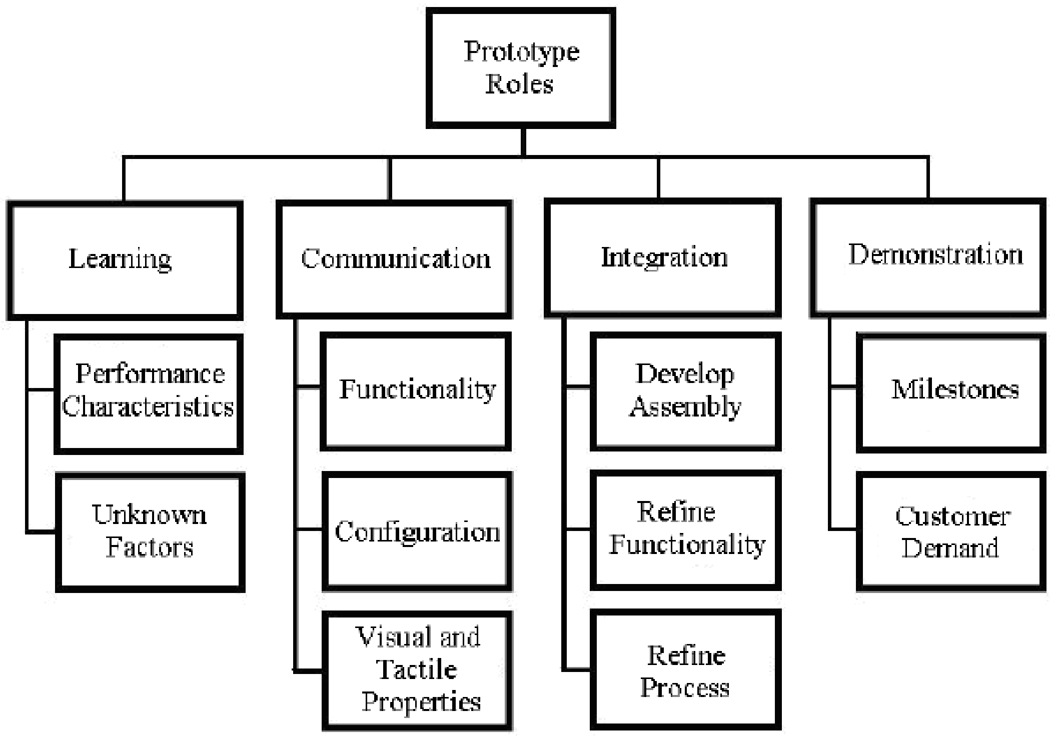

Figure 2: Roles of prototypes (9)

2.4. LITERATURE SURVEY

The product development process represents a significant investment in terms of research and development (R&D) resources. Many companies invest almost 2-8% of their sales into R&D. In spite of this research shows that about 40-60% of product development resources are invested in products that are cancelled or do not yield adequate results (2). In addition many products which enter the market have not been developed to their full extent (12). Given the financial implications product development decisions are crucial to the success of a company. Research has shown that effective prototyping decisions (e.g., the number concepts to prototype simultaneously, the number of iterations to pursue for a particular design concept) are critical aspects of a product development process and its success (2). Simultaneously it has been shown that the greatest portion of sunk cost during product development takes place during the prototyping phase (2). This indicates the importance given to prototyping in the product development process.

2.4.1 Advantages of Prototyping

The advantages and benefits prototyping have been studied and documented in detail over the past few years. Kelly (13) documents the art and process of innovation in IDEO (Palo Alto, CA), one of America's leading design firms, and extols the virtues of prototyping. An entire chapter is dedicated to prototyping; however, the author does not go into the specifics of how prototyping is accomplished internally. The author does not shed light on the specific tangible gains made from prototyping in their product design process. The author also does not elaborate upon the internal process which guides prototyping decisions.

A study of product development in the automobile industry recognizes that the ability to bring a solid product to the market quickly is crucial for success (14). It suggests that prototyping is very important and mentions some of the ways in which a product development process may go wrong. The study gives a brief overview of how certain parts may be prototyped. However, the book is written from a management perspective and does explain why certain prototyping strategies are more successful than the others.

A study of U.S. Department of Defense (DoD) design projects (15) over a 40 year period opines that under most conditions efficient prototyping proves to be beneficial for development programs. The authors list several benefits of prototyping such as (1) reduced technical risk; (2) validated designs; (3) evaluated manufacturing processes; (4) refined design requirements and (5) validated cost estimates. Citing anecdotal evidence the paper claims "prototyping provides a more complete experience for the design team". The authors claim that prototyping can help resolve the uncertainties involved with the initial requirements. An important aspect of this study is that they make an attempt to identify the exact conditions which favor prototyping. The following conditions are listed as being ideal for prototyping:

- Results are used to inform key decisions.
- The designer should make sure that the prototype is attempting to meet at least the minimum design requirements. If it is apparent that the requirements cannot be met then prototyping can prove to be counterproductive.
- The prototype is designed to demonstrate critical aspects of the final product in a realistic environment.
- The goal of the prototype should be to prove that the design can be successful in a real world environment. The prototype should also aim to meet design requirements apart from attempting to meet performance requirements.
- As of the prototyping stage there should be no commitment to production.
- Prototypes are experimental in nature. The testing results for prototypes may indicate that the objective requirements are not being met with accuracy. Hence the decisions regarding production should be made after a prototyping results are assimilated.
- No additional requirements are added once the prototyping for the product has started.
- Prototypes are geared to meet specific objective requirements. Increasing or adding specific requirements may encourage teams to rework existing designs, degrading the quality of the prototypes being built.

However, the report also cautions against allotting undue attention to prototyping efforts, as success of a product depends upon a variety of other factors and successful prototyping by itself cannot ensure success. While the paper does explain in depth the benefits of prototyping and the situations most suited for it, most of the conclusions reached in the paper are based on anecdotal evidence rather than proper scientific understanding. Also, the paper does not detail a structured method to implement prototyping once its use seems to be justified.

Another study (16) attempts to understand the psychological experiences of designers as a result of engaging in low fidelity prototyping. When designers attempt to create a large number of scaled prototypes at low resource cost, they quickly get feedback regarding the product and gain a better understanding of the user preferences early into the design process. The study details the following as the chief benefits of engaging in low fidelity prototyping:

- Failure is reframed as an opportunity for learning. Rapid and frequent prototyping supports the production of many ideas, thus minimizing the importance of any single idea or prototype. This sets the expectation that failure is an acceptable part of the product development process
- Fosters a sense of forward progress. Engaging in frequent prototyping allowed the design team to see forward progress in an innovation process in a short time. Progress was measured by shortening the product development timeline, which seemed to give designers a sense of accomplishment as they worked.
- Strengthens beliefs about creative ability. Design teams which employ low fidelity frequent prototyping can quickly communicate their ideas and build new ideas together which enhance group efficacy.

Though this research did discuss the benefits of prototyping, it did not attempt to quantify these supposed advantages. The study would have been more informative if the performance of teams employing low fidelity prototyping was compared against those that did not.

An interesting paper analyzing the effect of prototyping chose to focus on the process of knowledge acquisition through prototyping (17). The authors adopted a case study approach to study successful designs and consider the factors which led to successful designs. Some of the advantages of prototyping suggested by the paper are "examination of problems using a prototype clears prototype requirements," "multiple types of prototypes allow the problem to be seen from multiple perspectives" and "sometimes prototypes help clear inappropriate interpretation of a need." The case study further reinforced that prototypes help to detect problems before the final design.

The importance of prototyping in engineering design process is also further reflected in academic works dedicated to product design. Otto and Wood (10) discuss prototyping in great detail, including analytical modeling techniques, physical prototype processes and testing strategies to ensure that physical models meet design requirements. The book details the various uses of prototypes such as obtaining customer feedback, demonstrating design requirements, determining feasibility, scheduling, interfacing and system modeling. The authors also recognize that, while non-physical modeling is important, designers must develop and test physical prototypes to validate their designs. Another product design textbook by Ulrich and Eppinger (11) also focuses extensively on importance of prototyping in product development. An entire section is dedicated to the usefulness of physical prototypes versus nonphysical prototypes.

Learning through physical prototyping or model building is also consistent with the Experimental Learning Theory (ELT) developed by Kolb and Fry (18) , pioneers in the field of experimental learning. According to Kolb the process of learning occurs through four stages, as represented by the figure below. The four stages are:

1. Concrete experience (Direct practical experience);
2. Observation and reflection (Discussions and identification of unexpected difficulties arising from those experiences);
3. Forming abstract concepts (Critical thinking and analysis of what was observed); and
4. Active experimentation (Testing the analysis in the new situation).

ELT's focus on learning through practical experience can be viewed as an endorsement of model building or physical prototyping by engineering educators.

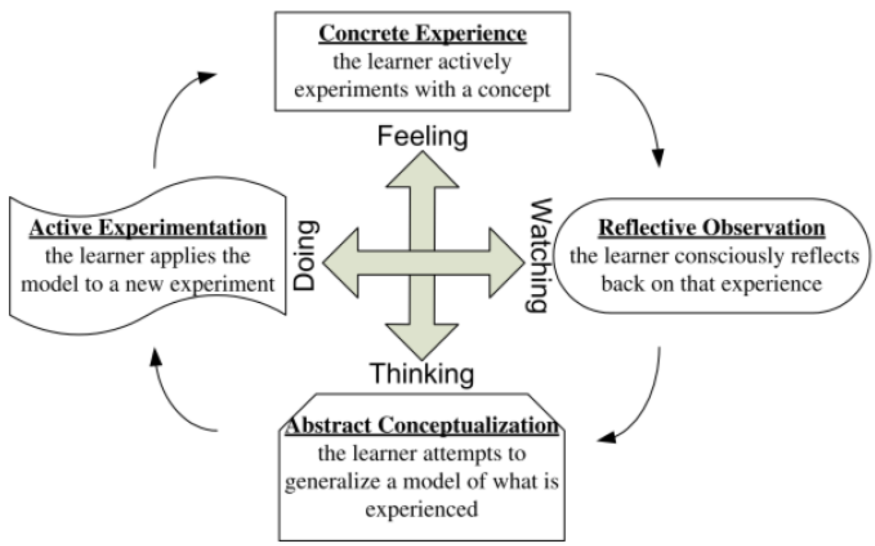

Figure 3: Four stages of Kolb's Experimental Learning (18).

2.4.2 Successful prototyping techniques

Apart from looking at the overall benefits of prototyping some research studies have attempted to study specific aspects of successful prototyping. Although these studies were focused on optimal prototyping from a management standpoint they provide several insights on aspects of prototyping which proved to be the most beneficial. Dahan and Mendelson (4) analyzed the effects of serial and sequential prototyping in different environments. Their recommendations suggested that sequential prototyping should be preferred in environments where cost was the primary barrier and parallel prototyping where time was more important. Thomke (19) documented the benefits of prototyping and identified situations in which certain techniques may be beneficial over others. His view suggests that prototyping yields benefits such as optimal cost and time savings when multiple technologies such as simulation and physical prototyping are used. Thomke and Bell (19) also suggested that significant cost savings can be realized by the use of multiple early prototypes instead of testing with a full developed final prototype. All these studies, while useful, do not comment on their relevance in academic design projects.

2.4.3 Prototyping in engineering curricula

Some studies focus on the specific context of design projects in engineering curricula. They serve as an excellent reference point for gauging the ideal prototyping environment for success of engineering design projects, particularly capstone design projects. Youmans (7) has investigated the effect of group work and prototyping on design fixation. The study looks at design fixation in people from engineering and non-engineering backgrounds, individually and in groups. The research study concluded physically interactive elements reduce fixation. The results indicated that participants who worked with interactive design materials fixated significantly less than participants who did not work with interactive design materials. It indicated that successful designers have a preference for interaction with physical materials whenever made available, with commensurate increase in model performance. The study also observed that physical interaction with material improved originality and functionality, resulting in more creative designs. The paper concludes design performance was significantly improved with the introduction of a complete design environment which allowed for physical construction and testing of a prototype by easing the cognitive burdens of the design task.

Kershaw, Otto and Lee (20) analyzed the effects of prototyping and critical feedback on fixation in engineering design. In their experiment, student groups were given different tasks across multiple design stages. Some of the groups were allowed to build more than one prototype early on, some were allowed to consistently improve their prototypes, some were not allowed to start on their physical prototypes until the end and some were not allowed to build any prototypes at all. The comparison between these groups was intended to document the effect of prototyping on engineering design. The study suggested that it was very difficult to identify the failures or other areas of improvements in a design without the construction of a prototype. The study hinted that the steady use of prototypes throughout the design process led to steady improvements throughout the design process. It supported Youmans (7) conclusion that designers can handle complex problems by reducing the cognitive load via prototyping. Hence the use of prototypes was supported in general.

Vishwanathan and Linsey (21) suggested fixation is not an inherent characteristic of physical representations but cost of building plays a role in fixation. The authors opine that fixation in physical modeling is caused due to the "sunk cost effect", which is the reluctance of designers to choose a different path once significant time and money is invested in the present one. The study observed that physical representations assist in overcoming flawed mental models of the designers. However, the study fails to comment on the interaction effect between the role of sunk cost and physical models, and the independent effect of each parameter is not determined.

Vishwanathan and Linsey (6) also investigated the role played by physical prototyping on design cognition. They conducted several controlled studies based on real world design problems. The results from their studies reflected that physical models help in correcting the erroneous mental models of students which resulted in a greater number of design solutions satisfying all of the project constraints. The authors indicate that, with the use of physical models, students can learn from their own mistakes, resulting in a more efficient method of education. They strongly advocate the promotion of physical modeling in general engineering curricula as it helps students to learn engineering concepts successfully. Based on these research studies Vishwanathan and Linsey (22) suggested that physical prototyping, if used correctly, has several benefits and hence designers need to be taught to use physical prototyping during idea generation for maximum results. This is an interesting observation which suggests that education regarding the optimum conditions suiting prototyping needs to be imparted to allow students to utilize its full benefit and steer them away from some of the disadvantages.

To analyze the effect of prototyping on concept generation a research study conducted introduced mandatory prototyping early in the design process (23). The researchers hypnotized that the use of physical prototyping early in the product design cycle could aid the concept generation process. The study consisted of two groups working on a particular design problem. One of the groups was asked to execute a two-week rapid prototype cycle at the start of their design. Comparison of the two groups showed that the introduction of an early prototyping stage was found to have some tangible benefit. Although the experimental group was found to develop a fewer unique solutions, the concepts developed were deemed to have greater feasibility than the control group. Also, comparison of the two teams revealed no evidence of design fixation in the experimental group, decrying the often stated view that the introduction of physical prototypes leads to design fixation. Additionally the experimental group also reported several qualitative advantages, including correct understanding of customer needs. However, the overall conclusions drawn by the research study were general in nature and, in order to draw specific conclusions on the positives and the negatives of an early prototyping experience, more research is needed.

Zemke (8) conducted a similar study which implemented a double prototype cycle in an engineering design class and reported upon the student learning from prototypes in the multiple prototype cycle. The paper suggested that multiple prototypes provide students with a safety net, thus allowing them to experiment more with their designs. They also suggested that multiple prototypes enhance the probability of success in a difficult project. Another interesting insight offered by this paper was that multiple prototype cycles allow layering of objectives, such as functionality and manufacturability among others, into different prototype cycles. This ensures that the students' design abilities are not taxed.

Zemke (24) also conducted a study in an intermediate level design class to identify the preconceptions that engineering students bring to a design class. The students were put through an entire design cycle consisting of mandatory physical prototyping and subsequent redesign stages. After the completion of their projects the students were told to discuss in depth their experiences in the design class and what they learned from it. The student feedback suggested that their incorrect assumptions frequently led to bad designs and physical prototypes need be assigned a high priority to test their designs against real world constraints. The study and the subsequent discussion stressed the fact that physical prototyping was highly essential and useful as it enforced real world constraints.

Lemons (25) analyzed the benefits of employing model building in engineering design. The study followed eight engineering students studying in various engineering colleges as they attempted to complete an open ended design task. A verbal protocol analysis was carried out to analyze the cognitive processes while performing the design task. The results of the verbal protocol analysis reiterated the belief that model building or physical prototyping helps students investigate the differences between real behavior and conceptual behavior. Model building as a part of an open ended design problem offered students the opportunities for creative thinking and helped in developing their metacognitive design skills. The only drawback of study was that it was based on a sample size of only eight engineering students. The data looks insufficient to draw significant results from the conclusions of this study.

Most of the studies reviewed justify the benefits of prototyping and discuss situations in which prototyping may be most appropriate. They either observe the designers' behaviors without external control or evaluate the effect of changing a single aspect of the prototyping in the overall design process. There is a lack of a method to implement prototyping to yield the most effective results. Based on this need, an efficient prototyping strategy development instrument was developed by a research group at UT Austin (3) (26). The details of this prototyping strategy tool are discussed in the next chapter. Statistically significant improvements were observed when this tool was tested at UT Austin and the United States Air Force Academy.

2.5. CONCLUSION

Although empirical evidence available from existing literature is conflicting to a certain degree, most of the papers suggest some tangible benefit is obtained through the use of physical prototypes in engineering design. This chapter presents a summary of the basics of prototyping and previous research reported in the literature on the use of physical models in engineering design from both business and engineering perspectives. Most of the literature surveyed discusses the advantages of prototypes and efficient techniques to implement prototyping. Another important point made by Vishwanathan and Linsey (22) is that students need to be educated about effective strategies to implement prototyping in order to yield the most tangible benefits. Based on the insights offered by these studies, it is clear that students can benefit from the use of physical prototypes. Students also need to be provided with appropriate tools and background information to make prototyping efforts successful. The research study reported in this thesis exposed undergraduate students in the Mechanical Engineering capstone design class at UT Austin to a prototyping strategy tool to gauge its impact on the prototyping effort. The subsequent chapters discuss the prototyping strategy tool and provide details of the studies conducted.

CHAPTER 3: RESEARCH METHODOLOGY

As detailed in the previous literature, prototyping is one of the most important phases of a product development process. Its implementation is often haphazard and based on previous experience rather than a well-defined decision making process. Most studies opine that tangible benefit is obtained through the use of physical prototypes. To encourage the use of physical prototypes in the capstone projects course and provide students with the relevant background information to make the prototyping effort successful, the students were exposed to a prototyping strategy tool described in detail in section 3.1. The prototyping strategy tool was developed by assimilating successful prototyping heuristics and practices. The goal was to provide the design teams a systematic approach to developing planned prototyping strategies.

3.1 PROTOTYPE STRATEGY DEVELOPMENT TOOL

The prototype strategy tool aims to provide designers a means to systematically make prototyping decisions (3). The inherent assumptions made in developing this prototyping strategy are (3):

1. An effective prototyping strategy attempts to exhaust all resources.
2. An efficient prototyping strategy attempts to maximize profit and/or design performance.
3. The more iterations of a single concept, the more likely that one of them will be successful at meeting the design requirements.
4. The more concepts that are developed in parallel, the greater the likelihood of choosing the correct concept.
5. The more experience a designer has, the greater the probability of developing a prototype that meets design requirements in the fewest possible prototype iterations.

The prototyping strategy tool leads designers through six main prototyping strategy decisions

1. How many concepts should be prototyped in parallel?
2. How many iterations of each concept should be built?
3. Should the prototype be virtual or physical?
4. Should subsystems be isolated?
5. Should the prototype be scaled?
6. Should the design requirements be temporarily relaxed?

Details of the variables, including the studies which prompted to the development of the decision making matrix for each variable, are given below.

Number of concepts to prototype in parallel: The exploration of parallel design concepts is essentially the development of multiple fundamentally different design concepts to achieve the same design objective during a product development project. In a study of industry cases, Badri (1) has identified that multiple research teams working concurrently on the same design problem enhances the design outcome. Thomke (27) finds that industry projects typically explored many concepts in parallel. However, the paper also suggests that information produced by each prototype needs to be integrated for maximum results. Ulrich and Eppinger (11) opine that the choice of developing prototypes, whether parallel or sequentially, is constrained by cost, benefit and time implications. Christie (26) has observed that developing multiple concepts at an early stage can help provide critical design feedback. An experiential study conducted by Dow (28) validated the idea that pursuit of multiple concepts leads to performance improvements. The research indicated that parallel concepts can significantly improve performance, improve concept evolution and reduce errors in design. However, the development of multiple concepts is limited by the constraints imposed by time and funding available to complete the project. Based on these insights a decision matrix and Likert scale (See Figure 4) are used in the prototyping strategy tool to help designers determine if the resources available are adequate to pursue multiple concepts. If the answers to these questions suggest that it is preferable to pursue multiple concepts, then teams must decide how many concepts to prototype in parallel.

		Strongly Disagree.	Disagree.	Neutral.	Agree.	Strongly Agree.
		-2	-1	0	1	2
A)	There are sufficient materials to prototype multiple concepts.					
B)	There is sufficient time to prototype multiple concepts.					
C)	Pugh rankings are close enough that multiple concepts show promise.					
	Use the sum of your responses to the above questions to determine whether a single or multiple concept(s) will be pursued (e.g., a positive sum would suggest pursuing multiple concepts).	One concept ←			Multiple concepts →	

Figure 4: Decision Matrix for Number of concepts

Number of iterations: Iteration in prototyping is defined as the cycle of creating, testing, and improving a single design concept. Several research studies discuss the effect of iterative prototyping on design outcome. A Department of Defense Study (15) identifies that prototypes can be used in build-test cycles to systematically advance towards a mature design. Glegg (29) has suggested that product development projects are best served when they go through three fundamental design iterations: the base idea, the first embodiment and the contemporary embodiment. Ulrich also discusses the choice between prototyping sequentially and in parallel. Ulrich suggests that the number of iterations to be feasibly pursued in a product development cycle may be given by the timeline of the project divided by the duration of a single prototyping cycle (11). Thomke (30) suggested that the cost of each iteration decreases as serial prototyping progresses. Vishwanathan and Linsey (21) also note that the overall number of prototypes produced by a team increases when teams are provided with less complex manufacturing processes. Dow (31) experimentally validated the effect of iteration on design performance. In this study, one group of teams was required to pursue at least three design iterations in the same time period as the teams in the other group only made one prototype. The results indicated that the group which created more than one prototype saw a significant improvement in performance as a result.

To summarize, previous studies show that exploring multiple iterations improves overall performance significantly, though its use is limited by resource constraints imposed upon the system. Based on these insights, a Likert scale (see Figure 5) was developed to help designers determine if available resources warrant the iteration of a design concept. In using the prototype strategy tool this process is repeated for each concept that is identified as a candidate for prototyping.

		Strongly Disagree.	Disagree.	Neutral.	Agree.	Strongly Agree.
		-2	-1	0	1	2
A)	The difficulty of meeting the requirements will necessitate iteration.					
B)	The difficulty of manufacturing will necessitate iterative prototyping.					
C)	My team has minimal prototyping experience.					
	Use the sum of your responses to the above questions to determine whether a single or multiple iterations will be pursued (e.g., a positive sum would suggest pursuing multiple iterations).	Do Not Iterate ←			Iterate →	

Figure 5: Decision matrix for number of iterations

Scaling: A scaled prototype is one in which certain attributes (typically geometry) have been reduced/increased while retaining the original proportions and maintaining the working principles of the system. Some studies have tried to identify the effect of scaled prototypes on design outcome. Vishwanathan (32), in a study intended to gauge the cognitive effects of physical prototypes on designers, noted that boundary conditions along with the prototypes need to be proportionately scaled to yield accurate results. The use of scaled prototypes is facilitated by the use of known dimensionless parameters or known scaling laws, eliminating this uncertainty in the results. Christie (26) noted that, in situations where creation of full size prototype is not feasible, such as building a ship or an aircraft, creation of scaled models is inevitable. Cho (33) has further explored the use of dimensionless groupings to use scaled models effectively. He suggests that multiple models may be constructed each scaled attribute of the final product. For example, the first model can be made by using the correct geometry but with materials that are easier to modify, while another model could be made using the materials of the final product but with simpler geometry. These research studies reflect the view that scaled models can provide valuable information while reducing costs and allowing complex designs to be prototyped easily. The Likert scale developed to help designers determine if constructing a scaled prototype would be optimal is given in Figure 6.

		Strongly disagree.	Disagree.	Neutral.	Agree.	Strongly Agree.
		-2	-1	0	1	2
A)	A known scaling law(s) will permit accurate knowledge to be gained by looking at a scaled model of the system?					
B)	Scaling will significantly simplify the prototype?					
	Use the graphical distribution of your responses to the above questions in order to determine whether to scale the design (e.g., a positive sum would suggest scaling the prototype).	← Do not scale			Scale the design →	

Figure 6: Decision matrix for scaling

Subsystem Isolation: Subsystem isolation refers to prototyping or modeling a a subsystem of the design to test its performance instead of prototyping the entire design concept. In certain cases it is feasible to produce only a few components of the entire system without having to produce the complete system. Subsystem isolation becomes particularly useful when certain components of the system undergo repetitive iteration without substantial changes to the overall design of the product. Subsystem isolation can also prove to be useful if any particular subsystem requires greater consideration in terms of prototyping resources over other subsystems. Christie (26) notes that when prototyping a large system, it is helpful to decompose the prototype into smaller components so that an optimal strategy can be developed for each component separately. This approach can also simplify the testing for several components. He cautions that this approach is feasible only when effective reintegration of the subsystems is possible. A Department of Defense case study (15) discusses in depth that certain systems, such as tanks, are too costly to prototype in their entirety until the production stage. The case study of an Air Force program indicated that it was possible to gather useful testing data from scaled prototypes for a fraction of the cost of a fully developed prototype. These studies show that subsystem isolation can be an effective method to prototype complex designs and allow testing of a subsystem for a fraction of the total cost. The Likert scale developed to guide designer's decisions in this respect is shown in Figure 7.

		Strongly disagree.	Disagree.	Neutral.	Agree.	Strongly Agree.
		-2	-1	0	1	2
A)	The interfaces between the subsystems are predictable and/or are NOT critical.					
B)	1 or 2 subsystems embody critical design requirements that will likely need iteration.					
C)	Prototyping a subsystem will significantly reduce time, cost or complexity compared to full system prototyping.					
D)	Can an isolated subsystem be properly tested?					
	Use the graphical distribution of your responses to the above questions in order to determine whether to isolate or integrate subsystems (e.g., a positive sum would suggest isolating subsystems).	Integrate Subsystems ←			Isolate Subsystems →	

Figure 7: Decision matrix for subsystem isolation

Requirement Relaxation: Requirement relaxation requires that a prototype fulfill only a percentage of the functional requirements of the product. The intention is to create a prototype to meet design requirements partially. In a case study of Department of Defense projects, Drezner observed that prototypes should focus specifically on the aspects of the prototype which are most uncertain (15). Thomke and Bell (30) have also looked at analytical models which can be used to analyze the importance of requirement relaxation. The analytical models show that significant cost saving can be achieved by the use of multiple low fidelity prototypes. The models indicate that tests with partial fidelity are advantageous when multiple low cost designs are evaluated. The background study indicates that requirement relaxation is an excellent approach to reduce costs and provide valuable information during design development. The Likert Scale developed to guide designers in the choice with reference to requirement relaxation is provided in figure 8.

		Strongly disagree.	Disagree.	Neutral.	Agree.	Strongly Agree.
		-2	-1	0	1	2
6. a)	The flexibility of the design requirements is such that they can be relaxed during prototyping and meaningful results can still be obtained?					
6. b)	Requirement relaxation will significantly simplify the prototype?					
	Use the graphical distribution of your responses to the above questions in order to determine whether to relax the design requirements (e.g., a positive sum would suggest scaling the prototype).	Do not relax				Relax the design requirments

Figure 8: Decision matrix for requirement relaxation

Virtual Prototyping: Virtual prototyping could be used to be simulate aspects of the real world behavior of physical products. Virtual prototyping is implemented through the use of analytical models and computer simulations. Ulrich and Eppinger (11) suggest that designers can select between virtual and physical prototyping depending upon constraints such as cost and time. The ratio of accuracy in the model required to the effort of construction can be used to guide the choice between the two. Virtual prototypes are particularly useful when physical prototyping and testing is prohibitively expensive. Virtual prototyping also allows flexibility in gathering data which would otherwise be infeasible in a physical model (34). Wang (35) mentions that one of the greatest benefits of virtual prototyping is that design can be integrated with testing. Wen (36) states that virtual models, particularly finite element models, can prove to be crucial in the identification of weak structural elements. Goldstein (37) discussed several scenarios where virtual models can be created within a few hours, where the creation of physical models within the same time period would be infeasible. Clin (38) claims virtual prototypes are more versatile in highly nonlinear and unique situations because they can be highly customizable. Virtual prototypes are assuming adding significance in product development given the increasing computational capacity available at reduced cost. However it is important to note that virtual prototypes do have some disadvantages which make physical prototypes more suitable for certain applications. In certain cases it may be easier and faster to make a physical model of the system. A virtual model only simulates phenomena which have been incorporated into the model. If a physical phenomenon which is relevant to the design is not included in the model then the effect of that phenomenon is ignored. The Likert scale for virtual vs. physical prototype is shown in Figure 9.

		Strongly Disagree.	Disagree.	Neutral.	Agree.	Strongly Agree.
		-2	-1	0	1	2
5 a)	Virtual prototype(s) will require less time than building physical prototype(s).					
5 b)	Virtual prototyping will be sufficiently accurate to model critical physics, or interfaces and/or help evaluate critical design requirements.					
5 c)	A CAD model is needed for advanced engineering analysis (FEA, CFD, etc.) or for manufacturing purposes.					
5 d)	There is sufficient time & budget to construct both virtual & physical prototypes.					
	Use the sum of your responses to the above questions to determine whether physical or virtual prototyping will be pursued (e.g., a positive sum would suggest pursuing virtual prototyping).	← Physical			Virtual →	

Figure 9: Decision matrix for virtual prototyping

	Compute the average response to the prompts under each category to determine strategy.	Strongly Disagree. -2	Disagree. -1	Neutral. 0	Agree. 1	Strongly Agree. 2
1	**For high avg, develop multiple concepts; else, build one only.**	**One Concept**				**Multiple Concepts**
a	There are sufficient materials to prototype multiple concepts.					
b	There is sufficient time to prototype multiple concepts.					
c	Rankings of several concepts are very close (e.g. from Pugh chart).					
2	**For a high avg, iterate; else, build once.**	**Do Not Iterate**				**Iterate**
a	The difficulty of meeting the requirements will necessitate iteration.					
b	The difficulty of manufacturing will necessitate iterative prototyping.					
c	My team has minimal prototyping experience.					
3	**For a high avg, use a virtual prototype; else, use physical models.**	**Physical**				**Virtual**
a	Virtual prototype(s) will require less time than a physical one(s).					
b	Virtual modeling will validate: physics, interfaces and/or requirements.					
c	A CAD model is needed for analysis (FEA, CFD, etc.) or manufacture.					
d	Time & budget allow pursuit of both virtual and physical prototypes.					
4	**For a high avg, isolate subsystems.; else, integrate the system.**	**Integrate Subsystems**				**Isolate Subsystems**
a	Interfaces between subsystems are predictable and/or are NOT critical.					
b	1 or 2 subsystems embody critical design requirements & need iteration.					
c	A subsystem build would significantly reduce time, cost or complexity.					
d	An isolated subsystem can be properly tested.					
5	**For a high avg, use a scaled model; else, use a full size model.**	**Do Not Scale**				**Scale**
a	Scaling law(s) will permit accurate system modeling via a scaled build.					
b	Scaling will significantly simplify the prototype.					
6	**For a high avg, relax requirements.; else, pursue full requirements.**	**Do Not Relax**				**Relax Design Requirements**
a	Requirement flexibility allows significant results from a relaxed model.					
b	Requirement relaxation will significantly simplify the prototype.					

Table 1: Complete prototyping strategy tool.

The complete prototyping strategy tool is shown in the table above. As can be seen in the table, each of the six variables has its own Likert scale to guide the user in choosing an approach for that prototyping decision. By answering the prompts the user obtains mapped scores for each of these questions. The magnitude of the score leads the designer to the choice that most appropriate for their project based on the heuristics described previously. If the answer to the questions leads to a neutral response the designers must reconsider their answers to the questions until one choice is better. The approach saves the designers considerable effort as the prototyping decisions have been reduced to critically thinking though the answers to the questions posed in the prototyping strategy tool.

3.2. EXPERIMENTAL EVALUATION

The efficacy of the prototyping strategy development tool was experimentally evaluated in the capstone design class in the Department of Mechanical Engineering at The University of Texas at Austin (UT Austin). This section details the research hypotheses and the experiment conducted to validate them. Before delving into the research methodology it is important to understand the structure of the capstone program at UT Austin in which the experiment was conducted.

3.2.1 COURSE DESCRIPTION

The capstone design program is an engineering design course which provides hands-on experience from industry-sponsored projects with real world design problems possibly aiming at patentable solutions and business plans for implementation. Although individual projects may differ the typical design activities fulfilled by students throughout the course of the project are as follows:

1. Define user requirements
2. Generate concepts and select the most promising concept
3. Create design and analysis models
4. Benchmark designs against existing products
5. Develop a prototype for design validation

It is important to note that some sponsors did not require prototypes to be built as part of their final deliverables. Hence it was particularly interesting to observe whether the students desire to implement and learn from physical prototyping even when it was not mandatory.

The course is structured with regular assignments, reports due throughout the semester with two major presentations – the design review and the final project presentation. The students are assigned an academic advisor (faculty member from the Cockrell School of Engineering at UT Austin) and an industrial advisor from the sponsor for technical support throughout their project. They are required to meet with their sponsors as often as possible. There relatively few formal lectures in the course, and most of the semester is spent in small group work.

There is wide variation in the average level of difficulty and the scope of the projects, which makes this an important study to gauge the overall effectiveness of the prototyping strategy tool. As mentioned earlier some project sponsors expect a working prototype as a deliverable while a virtual CAD model of the intended design suffices for some projects. For projects requiring a working prototype, teams often elect to build a single version and do not iteratively improve the prototype by testing and redesign.

3.2.2. Research Methodology

The key questions to be tested by this study were:

1. Does exposure to the prototyping strategy tool lead teams to create more prototypes?
2. Because of exposure to the prototyping strategy tool, do teams who are not required to submit a prototype as a deliverable choose to make one nonetheless?

To answer these questions , the teams were presented with a formal method to implement the prototyping strategy tool. These students served as the experimental group in the experiment. Teams from courses in the previous years served as the control group (because they were not exposed to the prototyping strategy tool). To obtain information on the prototyping efforts of the teams in the control group, reports from the previous capstone design projects were studied. Each report details each stage of the design project assigned to the team, including any physical prototyping during concept selection or concept development. While writing the reports the students were reminded that they would not get any credit for any aspect of the project which is not described in the reports. Hence it is fairly safe to assume that if a project report does not detail a prototype, the team did not conduct any physical prototyping. Generally, the project reports detailed the development of prototypes fairly explicitly, so little interpretation is required by the reader. The reports were studied until an asymptomatic trend emerged with respect to the average number of prototypes implemented per team.

The students of the capstone design class of the two most recent semesters served as the experimental group. The prototyping strategy was presented to each class early in the semester. The presentation described the use of the strategy tool in the context of engineering design projects with the help of an example. The presentation was structured as an interactive session and the student participants were encouraged to clarify any questions regarding the use of the strategy tool.

After presenting the integrated prototyping strategy guide, the students were encouraged to use this guide to aid them in making prototyping decisions in the context of their design project. At the end of the semester the students were asked to describe their prototyping experiences in a survey. The details of the number of prototypes built, types of prototypes and function of each prototype created were captured by the survey. The survey also collected feedback on the prototyping strategy guide itself in an effort to improve it.

3.3 SUMMARY

This chapter introduced the research methodology utilized to evaluate the effect of introducing the prototyping strategy tool on capstone design projects. The details of the tool itself including the rationale behind the use of Likert scale surveys to make each of those prototyping decisions was given. The following chapter presents the data collected and the analysis of the data with regards to the research hypotheses.

CHAPTER 4: RESULTS AND DISCUSSION

This chapter reports upon the results of the experiments carried out to evaluate the effect of implementing a prototype strategy development tool in a capstone design class. The data is reported and its interpretation with respect to the hypotheses is presented. As mentioned earlier the key hypotheses of this study were:

1. Does exposure to the prototyping strategy tool lead teams to create more prototypes?
2. Because of exposure to the prototyping strategy tool, do teams who are not required to submit a prototype as a deliverable choose to make on nonetheless?

To interpret the data, the Student's t-test was employed because the number of data points is greater than 30. This makes the t-test appropriate as it will converge to the use of normal Gaussian statistical analysis. The variable to be tested 'number of prototypes' assumes numerical values and hence a t-test is appropriate to test the difference of means for this variable. For the analysis a p value less than 0.05 was assumed to be sufficient to reject the null hypothesis and accept the alternate hypothesis with statistical significance.

To test hypothesis 1, the reports from the control group were analyzed to determine the average number of prototypes created per team. The reports from the last six semesters (2011-2013) were studied until an asymptomatic trend emerged with respect to the average number of prototypes made per team, as can be seen from Figure 10.

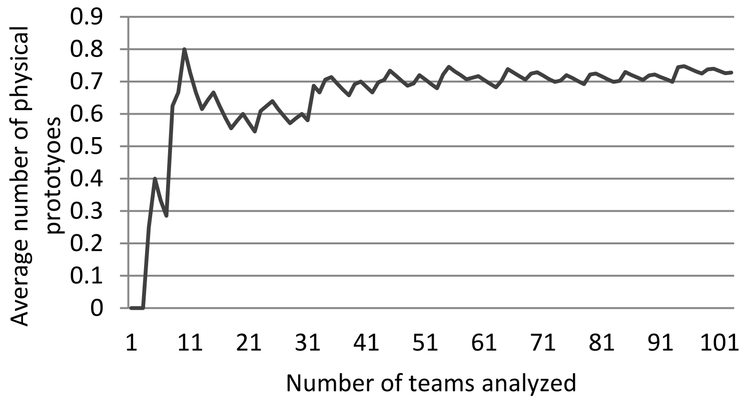

Figure 10: Average number of prototypes per team versus number of projects analyzed.

After analyzing about 100 project reports a clear asymptomatic trend emerged, approximately 0.7 prototypes per team. These results were compared with the 45 teams that were exposed to the prototyping strategy during the Spring 2014 and Fall 2014 semesters. Figure 11 compares the average number of physical prototypes per team reported by the experimental group compared to the analysis of the control group. The results show that on average these teams made 1.66 physical prototypes per team. The increase in the number of physical prototypes was statistically significant with a p value of 0.008.

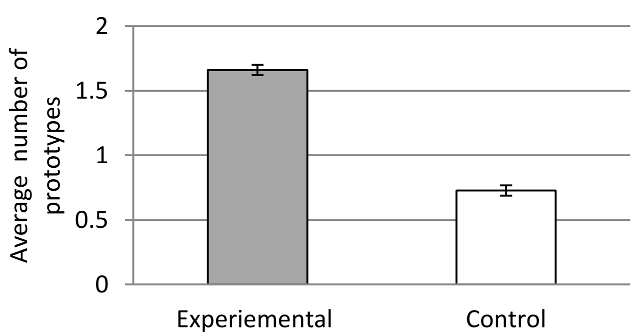

Figure 11: Comparison of average number of prototypes with ±1 error bar.

An important goal of using this prototyping strategy is encouraging students to choose to build prototypes where appropriate as part of the design process, even in cases where a prototype is not required by the sponsor. To test this hypothesis, the projects in both the experimental and control groups were divided into subgroups based on their deliverables. We determined the proportion of teams opting to construct at least one physical prototype that was not required. The results are documented in Figure 13.

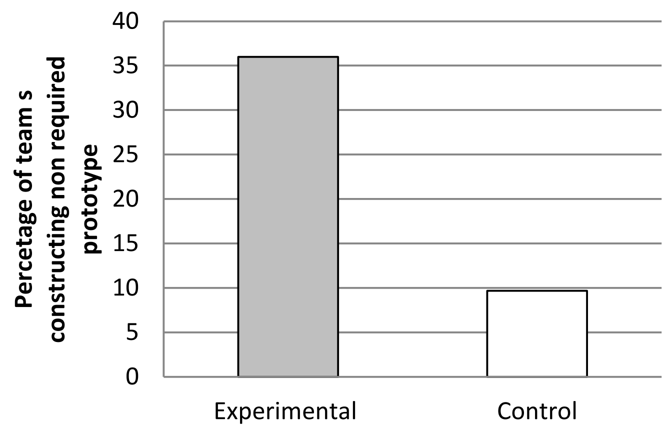

Figure 12: Comparison of proportion of teams opting to create non-required physical prototypes.

In the control group of previous design projects, 62 teams of those analyzed were not required to construct physical prototypes as a part of their final deliverables. Of these teams only 6 decided to build physical prototypes (about 10%). In the experimental group 25 teams were not required to build physical prototypes as part of the final deliverables. Of these, 10 chose to build physical prototypes (40%). This increase in the percentage of teams electing to construct physical prototypes was determined to be statistically significant with a p value of 0.0004.

As mentioned earlier, apart from the prototyping data the survey conducted for the experimental group collected feedback on the prototyping strategy guide and ways in which it could be improved. The feedback on the survey was collected in the form of questions which asked the students to rate a specific aspect of the prototyping strategy guide on a scale of 1-5. These questions were as follows

1. The strategy guide was easy to follow
2. The strategy guide is useful in helping my team formulate a prototyping strategy
3. The strategy guide helped my team consider aspects of prototyping that would have been overlooked
4. The strategy guide is an efficient tool for formalizing a strategy tool
5. The strategy guide is an important part of the design process.

A score of 4 or higher on these questions was determined as being a positive review of the survey.

These results are encouraging as they reflect that prototyping strategy guide was helpful for several teams. Of the 44 teams who provided feedback on the strategy 19 (about 44%) found that that guide was easy to follow. 13 of 44 teams (About 30%) found the tool helped them in formulating a prototyping strategy for the project. About 20% (9 of 44) provided feedback that the tool helped them consider aspects of prototyping that they might have overlooked initially. Most importantly 10 teams (about 23%) considered the prototyping strategy tool to be an important part of their design process.

The students also suggested ways in which the strategy guide could be improved in the future. Survey entries such as “Expose earlier in courses” and “We already started prototyping. Present earlier” suggests that maximum benefit would have been obtained if the prototyping strategy had been presented earlier in the semester. It was also suggested that prototyping strategy guide could be made mandatory to obtain maximum benefit. Survey entry “Focus on low resolution prototyping" , "Make helpful in initial prototyping" reflect that teams could benefit from focusing on low resolution prototyping.

4.1 DISCUSSION

The first hypothesis was intended to gauge if exposure to the prototyping tool would lead to inducing the designers to adopt positive prototyping techniques. The exposure to the prototyping strategy led to a statistically significant increase in the average number of prototypes developed. We believe exposure to the prototyping strategy emphasized the importance of physical prototypes to the designers. The exposure to a systematic prototyping tool to organize prototyping effort encouraged the use of multiple prototypes. This is indeed encouraging as several research studies have expounded on the benefits of implementing physical prototyping. The results reveal that students can be encouraged to implement prototyping to ensure that their designs follow real world constraints.

With regards to the second hypothesis, it was observed that the proportion of teams opting to make a physical prototype without being explicitly required to do also increased with statistical significance after exposure to the prototyping strategy. This result also indicates that the positive effects of prototyping can motivate a team to pursue prototyping even when the project sponsor does not mandate physical embodiment of the product.

The feedback collected reflects that teams benefitted from the prototype strategy guide. It is the view of the author that capstone teams would derive maximum benefit if the suggestions of the teams are incorporated into the strategy guide in the future.

CHAPTER 5: CONCLUSION AND FUTURE WORK

The thesis documents research findings on the implementation of a prototyping strategy development tool. Prototyping is one of the most important phases of a product development process and often represents a significant investment of resources on the part of the company (2). On surveying previous capstone projects it was found that in spite of the high importance of prototyping, most of the capstone design teams' implemented prototyping in a very ad hoc manner. Based on this evidence we hypothesized that capstone project students would benefit from being exposed to a structured prototyping strategy to help in understanding the importance of prototyping and provide them with a framework to implement it effectively. The students were exposed to a prototyping strategy tool developed at UT Austin which would help the students in making decisions regarding the key prototyping choices such as number of iterations, number of concepts, and scaling of prototypes.

The strategy was presented to the students in a structured manner. The chief goal of the research was to gauge whether exposure to a structured prototyping strategy would convey the importance of prototyping to the designers and eventually lead to the creation of more prototypes. In other words, the goal of the study was to find if exposure to the prototyping strategy is positively correlated with the number of physical prototypes made by undergraduate students in a capstone design project. The key hypotheses to study for this these were;

1. Does exposure to the prototyping strategy tool lead to more prototypes?
2. Do teams who are not required to submit a prototype as a deliverable choose to make on nonetheless?

The students in the capstone design class were introduced to the prototyping strategy tool over the two semesters by two graduate students. Data pertaining to the prototyping efforts made by these teams was collected at the end of each semester. These data was compared to the prototyping efforts made by earlier teams who had not been exposed to such a prototyping strategy. The data from previous capstone projects was obtained by studying their project reports. The results of the study are highly encouraging, as both the average number of prototypes and proportion of the teams opting for physical prototyping increased with statistical significance.

The first hypothesis was intended to gauge whether exposure to the prototyping tool would encourage designers to adopt positive prototyping techniques. The exposure to the prototyping strategy led to a statistically significant increase in the average number of prototypes developed. We believe exposure to the prototyping strategy emphasized the importance of physical prototypes to the designers.

It was also observed that the proportion of teams opting to make a physical prototype without being explicitly required to do also increased with statistical significance after exposure to the prototyping strategy. This result also indicates that the positive effects of prototyping can motivate a team to pursue prototyping even when the project sponsor does not mandate physical embodiment of the product. This further supports the belief that exposure to the prototyping strategy tool convinced the students of the importance of physical prototyping and encouraged them to make use of physical prototypes for validation with real world constraints. The results are encouraging as they indicate that students can be cautioned against over-reliance on virtual prototyping and encouraged to build physical prototypes by exposing them to a well-defined prototyping strategy tool.

5.1. LIMITATIONS

One possible shortcoming of the study is that the results are based on analysis of design projects in an academic domain. This makes generalizing the results difficult. However, as mentioned earlier, the capstone design program solicits projects from industry. The diversity in terms of both the types of industries sponsoring projects and the variety of the projects themselves offers some assurance that this has implications beyond academia.

Also, in this study the number of prototypes constructed is used as a metric to assess whether exposure to the prototyping strategy tool has persuaded designers to think about these critical prototyping decisions. This approach was adopted based on several research studies (7; 8; 6). However, future research should consider other metrics such as percentage of teams opting to construct scaled prototypes, or the number of teams opting to isolate subsystems in their prototypes.

5.2 FUTURE RESEARCH

Future work should focus on collecting data on other prototyping parameters such as subsystem isolation and prototype scaling. Other parameters could be used to evaluate the impact of the tool on the prototyping efforts of the capstone students. Examples of these could be cost of prototyping or non-numerical measures such as ease of prototyping. In the current research the students are just being exposed to the methods in a single presentation. Instead, the importance of prototyping could be made to be a topic of discussion in the regular interactions that the students have with their teaching assistants throughout the semester. It would be also be beneficial to seek better ways to assimilate prototyping methods into the design methodology that the students are taught. Another important avenue of research is improving the prototyping strategy development tool itself based on student feedback.

Appendix A – Prototype Strategy Guide

Use this document to formulate a prototyping strategy, and to update the strategy as prototypes are completed.

DEFINITIONS

Prototype – an approximation of a product design concept used to refine the design and help meet customer needs. A prototype can be used to embody and explore any aspect of the design using: concept sketches, low-resolution embodiment, analytical/mathematical models, virtual modeling, component testing, fully functional embodiment, etc.

> **Example:** *Prototypes of a student Formula SAE vehicle chassis might include: sketch on paper, PVC mock up, CAD model, and fully welded product. These are typically built one after the other (serial iterations.)*

Virtual Prototype - a computer based model (CAD model, motion analysis, FEA, CFD, etc.) of a product that can be used for visualization, analyzed and modified.

Physical Prototype – a tangible, physical model of a product or subsystem that can be analyzed, tested, and modified.
Subsystem Isolation – Often a subsystem of a design concept can be prototyped and evaluated in isolation.

> **Example:** *Monitor design project- prototype the LCD array but ignore casing design.*

Scaling – Prototype size is either larger or smaller than the planned final design size to reduce difficulty and/or cost, however it retains relative characteristics of the actual size form.

> **Example:** *A navy ship built 1/100 scale for initial water-tunnel testing.*

Design Requirement Relaxation – Prototypes may be built with "relaxed" design requirements to simplify the process.

> **Example:** *An initial engine prototype is made without concern for the amount of torque to save time and money while studying the basic power transfer component layout.*

Iterations – Building a prototype, testing and evaluating the prototype, refining the design concept, and re-building another prototype of that same concept is called "iterating".

Parallel vs. Serial – Parallel prototyping occurs when multiple concepts are built at the same time, unlike serial prototyping in which one prototype is followed by another. Single-lane roads allow cars to travel in serial and multi-lane roads allow cars to travel in parallel.

Prototyping Best Practices:

- ***Successful teams often initially prototype multiple different concepts.***
- ***Prototype early and often. Consider low-resolution prototypes to explore many concepts quickly and economically.***
- ***Keep prototypes as simple as possible while yielding the needed information, thereby saving time & money.***

Team Number: ___________________Date: _________________

Prototype Strategy Template

Use this page in conjunction with the "Prototype Strategy Guide (pages 3-7)" to formulate a prototype strategy. This page provides a framework for your strategy and should be filled in as you work through the guide. The numbers in the table below correspond to the numbers on the guide.

1. Fill in the names of the concepts:	Concept 1:	Concept 2:	Concept 3:	Concept 4:
Based on criteria 1a-c which concept(s) will you prototype first? (mark with 'X')				
2. # of iterations?				
3. Purpose of this Prototype iteration?				
4. Virtual or Physical Prototype?				
5. Isolate the Subsystems?				
6. Scale the Prototype?				
7. Relax the Design Requirements?				

Prototyping Strategy Guide

Use the guidelines below to develop a strategy. Fill in the blanks on the "Prototype Strategy" page to formalize your strategy

		Strongly Disagree.	Disagree.	Neutral.	Agree.	Strongly Agree.
		-2	-1	0	1	2
1. a)	There are sufficient materials to prototype multiple concepts.					
1. b)	There is sufficient time to prototype multiple concepts.					
1. c)	Pugh rankings are close enough that multiple concepts show promise.					
	Use the sum of your responses to the above questions to determine whether a single or multiple concept(s) will be pursued (e.g., a positive sum would suggest pursuing multiple concepts).	One concept			Multiple concepts	

1. Complete the following form based on the specific aspects of your design concepts.

Based upon the table above, discuss with your team which concept(s) your team will pursue**. Mark the chosen concept(s) in the space provided in the chart on page 2.**

Questions 2-7 will have unique answers for each concept. Accordingly, follow through the guide below for ***each chosen concept***:

2. How many additional iterations, beyond the initial prototype, do you think will be required to meet the design requirements? To make your estimate of the number of iterations, consider the difficulty of meeting the design requirements, the difficulty of manufacturing the prototype and your level of prototyping expertise. [Enter answer in table on page 2].

3. A prototype is often built and tested with the specific purpose of answering questions and refining the design. In the space provided in the chart on page 2, define your purpose for prototyping *this first iteration* of each *chosen* concept.

4. Use the form below to determine if a virtual or physical prototype will be built. (Reference the definition/example of *virtual and physical models* on pg 1.)

> **Points to Consider**
> For any approach that deviates from building a complete working model, be sure there is adequate time and budget for future iterations that meet all design requirements.

		Strongly Disagree.	Disagree.	Neutral.	Agree.	Strongly Agree.
		-2	-1	0	1	2
5 a)	Virtual prototype(s) will require less time than building physical prototype(s).					
5 b)	Virtual prototyping will be sufficiently accurate to model critical physics, or interfaces and/or help evaluate critical design requirements.					
5 c)	A CAD model is needed for advanced engineering analysis (FEA, CFD, etc.) or for manufacturing purposes.					
5 d)	There is sufficient time & budget to construct both virtual & physical prototypes.					
	Use the sum of your responses to the above questions to determine whether physical or virtual prototyping will be pursued (e.g., a positive sum would suggest pursuing virtual prototyping).	← Physical		Virtual →		

Based upon the chart above, will you build a virtual or physical prototype? Insert answer in the chart on page 2.

Prototyping Strategy Guide

5. Use the form below to determine if any subsystems will be isolated. (Reference the definition/example of *subsystem isolation* on pg 1.)

		Strongly disagree.	Disagree.	Neutral.	Agree.	Strongly Agree.
		-2	-1	0	1	2
4. a)	The interfaces between the subsystems are predictable and/or are NOT critical.					
4. b)	1 or 2 subsystems embody critical design requirements that will likely need iteration.					
4. c)	Prototyping a subsystem will significantly reduce time, cost or complexity compared to full system prototyping.					
4. d)	Can an isolated subsystem be properly tested?					
	Use the graphical distribution of your responses to the above questions in order to determine whether to isolate or integrate subsystems (e.g., a positive sum would suggest isolating subsystems).	← Integrate Subsystems			Isolate Subsystems →	

Based upon the chart above, will you isolate the subsystems? Insert answer in the chart on page 2.

Prototyping Strategy Guide

6. Use the form below to determine if the prototype will be scaled. (Reference the definition/example of *scaling* on pg 1.)

Points to Consider Scaling can be a function of adjusting size, loads, speeds, etc.		Strongly disagree.	Disagree.	Neutral.	Agree.	Strongly Agree.
		-2	-1	0	1	2
6. a)	A known scaling law(s) will permit accurate knowledge to be gained by looking at a scaled model of the system?					
6. b)	Scaling will significantly simplify the prototype?					
	Use the graphical distribution of your responses to the above questions in order to determine whether to scale the design (e.g., a positive sum would suggest scaling the prototype).	Do not scale ←			→ Scale the design	

Based upon the chart above, will you scale the prototype? Insert answer in the chart on page 2.

7. Use the form below to determine if the prototype will have relaxed design requirements. (Reference the definition/example of *design requirement relaxation isolation* on pg 1.)

> **Points to Consider**
> There is, to some degree, error inherit in each of the decision criteria. Consider if your formulated strategy will produce prototypes with error that would render the prototypes inadequate.

		Strongly disagree.	Disagree.	Neutral.	Agree.	Strongly Agree.
		-2	-1	0	1	2
6. a)	The flexibility of the design requirements is such that they can be relaxed during prototyping and meaningful results can still be obtained?					
6. b)	Requirement relaxation will significantly simplify the prototype?					
	Use the graphical distribution of your responses to the above questions in order to determine whether to relax the design requirements (e.g., a positive sum would suggest scaling the prototype).	← Do not relax			Relax the design requirments →	

Based upon the chart above, will you relax the prototype design requirements? Insert answer in the chart on page 2.

Now that you have completed a prototyping strategy, you have a clear direction on how to proceed into the **first iteration** of your concept(s). *For every subsequent iteration it is advisable for you to rework this method and update your strategy accordingly*. This is important because with each prototype iteration you will learn new things that could alter the course of your development work.

EXAMPLE

Prototype Strategy (See page 2 for template)

1. Fill in the names of the ranked concepts:	**Concept 1:** *Spring Leg*	**Concept 2:** *Hinged Ankle*	**Concept 3:** *Rigid Leg*	**Concept 4:**
Based on criteria 1a-d which concept(s) will you prototype first? (X)	**X**		**X**	
2. # of iterations?	*4 more iterations (1. Manufacture and test spring, 2. Test ground interface material. 3….)*	*4 more iterations (1. CAD model new hinge and optimize for strength, 2. Build and test full feature model 3…..)*	*2 more iterations (1. Build a clean comfortable model and test, 2. Build for manufacturing)*	
3. Purpose of Prototype?	*Determine spring stiffness necessary to support user during walking*	*Use off the shelf parts to determine joint locations*	*Quick mock up to see if this is even a feasible concept in terms of body alignment and mobility.*	
4. Virtual or Physical Prototype?	*Virtual*	*Physical*	*Physical*	
5. Isolate a Subsystem?	*Isolate the subsystems (Just looking at the load bearing spring. Not concerned with connecting leg to person)*	*Integrate the subsystems (Include all subsystems)*	*Integrate the subsystems (Include all subsystems)*	
6. Scale the Prototype?	*Do not scale*	*Do not scale*	*Do not scale*	
7. Relax the Design Requirements?	*Do not relax the design requirements (Use full scale forces in CAD model)*	*Relax the design requirements (Not concerned with aesthetics or long term performance)*	*Relax the design requirements (Not concerned with comfort of attachment for this version)*	

Appendix B – End of Semester Survey

Q#	Please answer the following questions by circling (or filling in) the most appropriate response	Strongly Disagree.	Disagree.	Neutral.	Agree.	Strongly Agree.
Assess your own activities (1-8)						
1	You adhered to the prototyping strategy closely.	1	2	3	4	5
2	You had sufficient time to complete the project.	1	2	3	4	5
3	You had sufficient budget to complete the project.	1	2	3	4	5
4	Your prototyping process was effective.	1	2	3	4	5
5	How many physical prototypes did your team build?(including proof of concept models)	# prototypes __________				
6	Were you required to submit a prototype as a deliverable?	No				Yes
7	Did your attitude towards prototyping change after exposure to the strategy?	No				Yes
8	Did exposure to the strategy method cause you to develop more prototypes than you expected beforehand?	No				Yes
Assess the strategy guide in general (9-13)						
9	The strategy guide is easy to follow.	1	2	3	4	5
10	The strategy guide is useful in helping my team formulate a prototyping strategy.	1	2	3	4	5
11	The strategy guide helped my team consider aspects of prototyping that would have otherwise been overlooked.	1	2	3	4	5
12	The strategy guide is an efficient tool for formalizing a prototyping strategy.	1	2	3	4	5
13	The strategy guide is an important part of the design process.	1	2	3	4	5
14	Please list a few things you **LIKE** about the prototype strategy development guide.	14-a 14-b 14-c				
15	In your opinion what possible improvements could be made to the prototyping strategy in its current form.	15-a 15-b 15-c				

Make a unique entry for each iteration of each concept in a new row. You may be left with empty rows, or request more sheets if needed.

Concept or iteration #	**Description (concept name, # of iterations)**	**Purpose (testing, aesthetics, functional)**	**Physical or virtual (CAD program or material)**	**Scaled (Y/N)**	**Isolated (Y/N)**	**Relaxed (Y/N)**	**Quality of prototype performance (1-10, 10 is high quality)**	**Usefulness (information gained) (1-10, 10 is very useful)**
I								
II								
III								
IV								
V								
VI								
VII								
VIII								
IX								
1X								

Appendix C – Prototyping Data

Control Group (Teams not exposed to the prototyping strategy)

Team Name	Year	Category	Number of Prototypes
Team 1	2011	Physical Prototype Not required	0
Team 2	2011	Physical Prototype Not required	0
Team 3	2011	Physical Prototype Not required	0
Team 4	2011	Physical Prototype Not required	0
Team 5	2011	Physical Prototype Not required	0
Team 6	2011	Physical Prototype Not required	3
Team 7	2011	Physical Prototype Not required	0
Team 8	2011	Physical Prototype Not required	0
Team 9	2011	Physical Prototype Not required	0
Team 10	2011	Physical Prototype Required	1
Team 11	2011	Physical Prototype Required	1
Team 12	2011	Physical Prototype Required	1
Team 13	2011	Physical Prototype Required	2
Team 14	2011	Physical Prototype Required	1
Team 15	2011	Physical Prototype Required	1
Team 16	2011	Physical Prototype Required	1
Team 17	2011	Physical Prototype Required	1
Team 18	2011	Physical Prototype Required	1
Team 19	2011	Physical Prototype Required	1
Team 20	2011	Physical Prototype Required	1
Team 21	2012	Physical prototype required	1
Team 22	2012	Physical prototype required	2
Team 23	2012	Physical prototype required	1
Team 24	2012	Physical prototype required	2
Team 25	2012	Physical prototype required	1
Team 26	2012	Physical prototype required	1
Team 27	2012	Physical prototype required	2

Team 28	2012	Physical prototype required	1
Team 29	2012	Physical prototype required	2
Team 30	2012	Physical prototype required	3
Team 31	2012	Physical prototype required	2
Team 32	2012	Physical prototype required	1
Team 33	2012	Physical prototype required	1
Team 34	2013	Physical prototype required	2
Team 35	2013	Physical prototype required	4
Team 36	2013	Physical prototype required	2
Team 37	2013	Physical prototype required	1
Team 38	2013	Physical prototype required	1
Team 39	2013	Physical prototype required	2
Team 40	2013	Physical prototype required	3
Team 41	2013	Physical prototype required	1
Team 42	2013	Physical prototype required	1
Team 43	2013	Physical prototype required	5
Team 44	2013	Physical prototype required	1
Team 45	2013	Physical prototype required	2
Team 46	2013	Physical Prototype Not required	0
Team 47	2013	Physical Prototype Not required	0
Team 48	2013	Physical Prototype Not required	0
Team 49	2013	Physical Prototype Not required	0
Team 50	2013	Physical Prototype Not required	0
Team 51	2013	Physical Prototype Not required	2
Team 52	2013	Physical Prototype Not required	0
Team 53	2013	Physical Prototype Not required	0
Team 54	2013	Physical Prototype Not required	0
Team 55	2013	Physical Prototype Not required	0
Team 56	2013	Physical Prototype Not required	4
Team 57	2013	Physical Prototype Not required	0
Team 58	2013	Physical Prototype Not required	0
Team 59	2013	Physical Prototype Not required	0
Team 60	2013	Physical Prototype Not required	0
Team 61	2013	Physical Prototype Not required	0
Team 62	2013	Physical Prototype Not required	0
Team 63	2013	Physical Prototype Not required	2
Team 64	2013	Physical Prototype Not required	0

Team 65	2012	Physical Prototype Not required	0
Team 66	2012	Physical Prototype Not required	0
Team 67	2012	Physical Prototype Not required	0
Team 68	2012	Physical Prototype Not required	0
Team 69	2012	Physical Prototype Not required	0
Team 70	2012	Physical Prototype Not required	0
Team 71	2012	Physical Prototype Not required	0
Team 72	2012	Physical Prototype Not required	0
Team 73	2012	Physical Prototype Not required	0
Team 74	2012	Physical Prototype Not required	0
Team 75	2012	Physical Prototype Not required	0
Team 76	2012	Physical Prototype Not required	0
Team 77	2012	Physical Prototype Not required	0
Team 78	2012	Physical Prototype Not required	0
Team 79	2012	Physical Prototype Not required	0
Team 80	2012	Physical Prototype Not required	0
Team 81	2010	Physical Prototype Required	5
Team 82	2010	Physical Prototype Required	1
Team 83	2010	Physical Prototype Required	2
Team 84	2010	Physical Prototype Required	1
Team 85	2010	Physical Prototype Required	1
Team 86	2010	Physical Prototype not required	0
Team 87	2010	Physical Prototype not required	0
Team 88	2010	Physical Prototype not required	0
Team 89	2010	Physical Prototype not required	0
Team 90	2010	Physical Prototype not required	0
Team 91	2010	Physical Prototype not required	0
Team 92	2010	Physical Prototype not required	0
Team 93	2010	Physical Prototype not required	0
Team 94	2010	Physical Prototype not required	0
Team 95	2010	Physical Prototype not required	0
Team 96	2010	Physical Prototype not required	0
Team 97	2010	Physical Prototype not required	0
Team 98	2010	Physical Prototype not required	0
Team 99	2010	Physical Prototype not required	0
Team 100	2010	Physical Prototype not required	0
Team 101	2010	Physical Prototype not required	0

Team 102	2010	Physical Prototype not required	0
Team 103	2010	Physical Prototype not required	0

Experimental Group (Teams exposed to the prototyping strategy)

Team Name	Year	Category	Number of Prototypes
Team 1	2014	Physical Prototype Required	6
Team 2	2014	Physical Prototype Not required	0
Team 3	2014	Physical Prototype Required	4
Team 4	2014	Physical Prototype Not required	0
Team 5	2014	Physical Prototype Required	1
Team 6	2014	Physical Prototype Required	6
Team 7	2014	Physical Prototype Required	3
Team 8	2014	Physical Prototype Not required	4
Team 9	2014	Physical Prototype Not required	0
Team 10	2014	Physical Prototype Required	3
Team 11	2014	Physical Prototype Required	3
Team 12	2014	Physical Prototype Required	1
Team 13	2014	Physical Prototype Required	1
Team 14	2014	Physical Prototype Required	2
Team 15	2014	Physical Prototype Required	3
Team 16	2014	Physical Prototype Required	2
Team 17	2014	Physical Prototype Required	2
Team 18	2014	Physical Prototype Required	0
Team 19	2014	Physical Prototype Not required	0
Team 20	2014	Physical Prototype Not required	0
Team 21	2014	Physical Prototype Not required	0
Team 22	2014	Physical Prototype Not required	0
Team 23	2014	Physical Prototype Not required	0
Team 24	2014	Physical Prototype Not required	3
Team 25	2014	Physical Prototype Not required	0
Team 26	2014	Physical Prototype Not required	0
Team 27	2014	Physical Prototype Not required	1
Team 28	2014	Physical Prototype Not required	0
Team 29	2014	Physical Prototype Not required	0
Team 30	2014	Physical Prototype Not required	1
Team 31	2014	Physical Prototype Not required	0

Team 32	2014	Physical Prototype Required	2
Team 33	2014	Physical Prototype Not required	1
Team 34	2014	Physical Prototype Required	1
Team 35	2014	Physical Prototype Required	7
Team 36	2014	Physical Prototype Not required	5
Team 37	2014	Physical Prototype Not required	0
Team 38	2014	Physical Prototype Required	1
Team 39	2014	Physical Prototype Not required	1
Team 40	2014	Physical Prototype Required	1
Team 41	2014	Physical Prototype Not required	4
Team 42	2014	Physical Prototype Not required	4
Team 43	2014	Physical Prototype Required	1
Team 44	2014	Physical Prototype Not required	0
Team 45	2014	Physical Prototype Not required	1

Appendix D – Prototyping strategy feedback

Control Group (Teams not exposed to the prototyping strategy)

Sr.No	The strategy guide is easy to follow	The strategy guide is useful in helping my team formulate a prototyping strategy	The strategy guide helped consider aspects that could have been overlooked	The strategy guide is an efficient tool for formalizing a strategy tool	The strategy guide is an important part of the design process.
1	3	4	4	4	4
2	4	4	4	4	5
3	4	4	3	3	3
4	3	3	3	3	3
5	4	3	2	3	3
6	3	3	3	3	2
7	3	4	4	4	4
8	4	3	3	4	3
9	4	4	3	4	4
10	3	2	2	3	2
11	4	3	2	3	3
12	3	3	2	3	2
13	3	2	2	2	2
14	3	3	3	3	3
15	3	3	3	3	3
16	3	3	3	3	3
17	4	3	3	3	3
18	3	3	3	3	3

19	3	3	3	3	3
20	4	3	3	3	3
21	4	4	4	4	4
22	4	5	5	4	5
23	3	3	3	3	3
24	4	1	1	4	4
25	3	3	3	3	3
26	4	3	3	4	4
27	3	3	3	3	3
28	3	3	3	3	3
29	1	1	1	1	1
30	3	3	3	3	3
31	4	4	4	4	3
32	4	4	4	4	4
33	4	3	2	4	4
34	4	4	3	3	3
35	3	3	2	3	3
36	3	3	3	3	3
37	3	1	1	3	3
38	3	3	3	3	3
39	4	4	4	3	3
40	4	4	3	4	3
41	1	1	1	1	1
42	1	1	1	1	1
43	4	4	4	4	1
44	3	3	3	3	3

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Vita

Tanmay Pramod Gurjar was born in Pune, India. He completed almost all of his early schooling in Mumbai. After high school he chose to pursue his undergraduate degree in Mechanical Engineering at College of Engineering, Pune (COEP). During his time there he chose to pursue several meaningful projects including design of an All-Terrain Vehicle which stood first in a collegiate competition. At COEP he also pursued rowing and took active participation in organization of several Boat Club Events. Upon graduation from COEP in 2013 he chose to attend The University of Texas at Austin as a graduate student. After completing graduate school, Tanmay will be working with Schlumberger as a Mechanical Design Engineer at their Katy location.

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